

## Estimating Dissolved Phosphorus Concentrations in Runoff from Three Physiographic Regions of Virginia

C. J. Penn,\* G. L. Mullins, L. W. Zelazny, and A. N. Sharpley

### ABSTRACT

The relationship between STP (soil test P) and DRP (dissolved reactive P) in runoff has been shown to vary with soil type due to differences in soil properties. The purpose of this study was to determine if soil tests could indirectly take into account differences in soil properties and thus provide one relationship with STP and runoff DRP among a variety of soil types. Nine different soil types were sampled from four different fields to provide a range in STP. Unamended soils were packed into runoff boxes for use in a rainfall simulation study. All soils were analyzed for P, Al, and Fe using various extractions, and correlated to runoff DRP concentrations from all soils when grouped based on soil type and physiographic region. Slopes and intercepts were unique to soil type for the STP vs. runoff DRP relationship among all soil P tests except for WSP (water-soluble P) slopes, resulting in an overall universal slope of  $0.0125 \text{ mg DRP L}^{-1}$ , which agrees with past studies. The y intercepts from the soil WSP vs. runoff DRP relationship were well related to soil clay content (negative relationship) in addition to the fact that Coastal Plain soils had a significantly greater y intercept than Piedmont and Ridge and Valley soils when grouped by physiographic region. This suggests that Coastal Plain soils possess a greater potential for releasing DRP into runoff compared with Ridge and Valley and Piedmont soil at equivalent WSP values. This study provides a means with which to estimate potential runoff DRP concentrations by use of soil WSP and clay content.

INCREASED P concentrations to surface waters typically stimulate algal production and eutrophication (Kennedy et al., 2002). The degradation of water quality in the Chesapeake Bay and other surface waters in the Mid-Atlantic region is attributed in part to increased loading of P (Coale et al., 2002). In addition, agriculture is considered an important nonpoint P source for both particulate (erosion) and dissolved forms to surface waters. Although erosion control can significantly reduce bioavailable P (Uusitalo et al., 2003) and total P (Sharpley and Kleinman, 2003) losses, significant losses of dissolved P can still occur when erosion is kept to a minimum (Sharpley, 1995; Daniel et al., 1994). Dissolved P losses in runoff have been shown to be well related to soil P concentrations and the degree of P saturation onto soil Fe and Al (Sims et al., 2002; Pote et al., 1996; Sharpley

et al., 1977). Thus, soils with high concentrations of extractable P are considered to be at a greater risk of causing nonpoint dissolved P losses than low-P soils.

Because of the increased awareness in regard to P losses from agricultural soils to surface waters, various P loss prediction models and P index tools have been developed (Karpinets et al., 2004; Vadas and Sims, 2002; Lemunyon and Gilbert, 1993) and often incorporate the relationship between extractable soil P and runoff dissolved P concentrations. The closeness of the relationship between P in solution, P leaching, and P in runoff with STP depends on the range of soils studied as well as the extractants used. These correlations are usually strong when the studied soils are fairly homogeneous in soil properties such as texture and pH (Sims et al., 1998; Yuan and Lavkulich, 1995; Lookman et al., 1996; Pote et al., 1996). As a result, recent studies have concluded that the relationship between extractable soil P and runoff dissolved P will vary with soil type (Torbert et al., 2002; Pote et al., 1999; Sharpley, 1995).

Penn et al. (2005) suggested that among soils not amended with P, variability in the soil P vs. dissolved P relationship could be due in part to differences in clay mineral type and quantity. This observation is attributed to the fact that phosphate sorption is primarily a result of ligand exchange reactions between hydroxyls exposed on the surfaces of minerals and the phosphate molecule in soil solution. Although they showed that the relationship between soil WSP and runoff DRP among nine soil types could be reduced to two regression equations based on soil HIV (hydroxy-interlayered vermiculite) and kaolinite content, analysis of soil mineralogy for this purpose would not be practical.

Therefore, a "universal" soil extractant capable of creating one relationship between soil P and runoff dissolved P regardless of soil type would be useful as a component in P prediction models. In theory, a universal soil extractant would indirectly take into account different P forms and soil mineralogy by primarily removing P from soil minerals that retain P with the least strength during a runoff event. The objectives of this study were to evaluate the use of various soil P extractants in predicting runoff P losses from selected agricultural soils of the Piedmont, Coastal Plain, and Ridge and Valley physiographic regions of Virginia.

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Published in Soil Sci. Soc. Am. J. 70:1967–1974 (2006).  
Nutrient Management & Soil & Plant Analysis and Soil & Water Management & Conservation  
doi:10.2136/sssaj2006.0027

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**Abbreviations:** DPS, degree of phosphorus saturation; DRP, dissolved reactive phosphorus; Fe-strip P, iron strip extractable phosphorus; HIV, hydroxy-interlayered vermiculite; M1-P, Mehlich-1 phosphorus; M3-P, M3-Al, and M3-Fe, Mehlich-3 extractable phosphorus, aluminum, and iron, respectively;  $P_{ox}$ ,  $Al_{ox}$ , and  $Fe_{ox}$ , ammonium oxalate extractable phosphorus, aluminum, and iron, respectively;  $Psat_{M3}$  and  $Psat_{ox}$ , phosphorus saturation ratio as determined by Mehlich 3 and ammonium oxalate, respectively; STP, soil test phosphorus; WSP, water-soluble phosphorus.

## MATERIALS AND METHODS

### Soil Collection and Characterization

Nine soil types were chosen to represent the major agricultural soils of the Piedmont, Coastal Plain, and Ridge and Valley provinces of Virginia (three soil types from each province). Four soil samples (four different fields) were collected within each soil type to provide a range in M1-P (Mehlich-1 extractable P) of  $<18$  to  $>55$  mg P kg<sup>-1</sup> ( $>55$  is considered high in regard to plant P requirements according to the soil testing guidelines of Virginia Tech). One exception was the Bojac soil type of the Coastal Plain, of which only three different samples were collected. Only soils that had not received any sort of P fertilization within 1 yr before collection were used in this study. A summary of relevant soil properties are shown in Table 1. These soils are the same as those described by Penn et al. (2005) and consist of the Piedmont soils Cecil (fine, kaolinitic, thermic Typic Kanhapludult), Tatum (fine, mixed, semiactive, thermic Typic Hapludult), and Davidson

(fine, kaolinitic, thermic Rhodic Kandiudult); Coastal Plain soils Emporia (fine-loamy, siliceous, subactive, thermic Typic Hapludult), Slagle (fine-loamy, siliceous, subactive, thermic Aquic Hapludult), and Bojac (coarse-loamy, mixed, semiactive, thermic Typic Hapludult); and Ridge and Valley soils Frederick (fine, mixed, semiactive, mesic Typic Paleudult), Groseclose (fine, mixed, semiactive, mesic Typic Hapludult), and Sequoia (fine, mixed, semiactive, mesic Typic Hapludult).

Soils were collected by sampling the top 0 to 5 cm of the topsoil; samples were air dried and sieved to 19 mm for later use in the rainfall simulation study. Subsamples of each soil type were further sieved to 2 mm for characterization. Soil characterization consisted of (i) pH (1:1 soil/solution ratio); (ii) sand, silt, and clay by the hydrometer method (Day, 1965); (iii) M1-P (1:4 soil/0.05 M HCl + 0.0125 M H<sub>2</sub>SO<sub>4</sub>, 5-min reaction time, filtration with Whatman no. 2 paper [Kuo, 1996]); (iv) WSP (1:10 soil/deionized water, 1-h reaction time, filtration with 0.45-μm Millipore membrane [Kuo, 1996]); (v) P<sub>ox</sub>, Al<sub>ox</sub>, and Fe<sub>ox</sub> (oxalate-extractable P, Al, and Fe, 1:40 soil/0.2 M acid

**Table 1.** Properties of the soils used in the simulated rainfall experiment and concentration of DRP (dissolved reactive P) measured in runoff for each soil. Values are the average of three replications. LSD = least significant difference based on a *P* value of 0.05.

Physiographic region	Soil type	WSP <sup>†</sup>	M1-P <sup>‡</sup>	M3-P <sup>§</sup>	M3-Al	M3-Fe	Psat <sub>M3</sub> <sup>  </sup>	Fe strip P	P <sub>ox</sub> <sup>#</sup>	Al <sub>ox</sub>	Fe <sub>ox</sub>	Psat <sub>ox</sub> <sup>††</sup>	Clay	pH	Runoff DRP
		mg kg <sup>-1</sup>							mg kg <sup>-1</sup>				%		mg L <sup>-1</sup>
Ridge and Valley	Frederick A	3.2	10	27	731	154	0.028	7	137	764	1160	0.019	39.4	5.7	0.156
	Frederick B	11.9	88	141	723	210	0.144	35	282	650	724	0.059	23.9	6.1	0.281
	Frederick C	15.8	47	139	681	210	0.150	37	239	541	569	0.063	20.2	7.1	0.295
	Frederick D	15.4	115	234	1228	197	0.149	78	524	1575	1040	0.069	30.7	5.5	0.290
	LSD <sub>0.05</sub>	0.7	4	10	63	15	0.001	3	35	174	189	0.004	1.9	0.1	0.031
Ridge and Valley	Groseclose A	4.7	11	51	737	172	0.052	11	158	746	1004	0.025	18.7	6.3	0.172
	Groseclose B	10.4	52	82	662	99	0.098	28	145	471	325	0.062	27.9	7.0	0.271
	Groseclose C	20.1	82	170	713	167	0.181	60	289	649	529	0.079	23.2	6.5	0.334
	Groseclose D	23.8	92	186	621	243	0.213	70	317	521	640	0.077	17.9	6.2	0.307
	LSD <sub>0.05</sub>	1.1	1	5	16	7	0.005	8	17	133	145	0.024	0.8	0.1	0.021
Ridge and Valley	Sequoia A	6.3	23	63	715	283	0.062	25	210	633	1637	0.021	42.3	6.2	0.163
	Sequoia B	8.3	35	84	781	160	0.083	34	190	717	740	0.039	36.3	6.3	0.194
	Sequoia C	13.7	44	74	631	202	0.086	46	215	537	1067	0.033	38.9	5.6	0.245
	Sequoia D	10.3	73	94	767	164	0.094	39	267	765	1170	0.036	46.6	6.3	0.223
	LSD <sub>0.05</sub>	0.3	5	6	42	10	0.004	10	37	169	235	0.004	0.7	0.1	0.034
Piedmont	Davidson A	2.8	6	19	870	205	0.016	7	102	966	1667	0.010	30.8	5.5	0.102
	Davidson B	4.6	27	49	1175	105	0.033	32	301	1902	1551	0.028	53.6	6.4	0.149
	Davidson C	8.3	19	50	660	120	0.059	21	198	840	1678	0.019	29.0	6.2	0.161
	Davidson D	16.9	28	73	618	102	0.093	53	433	1420	2116	0.032	45.8	6.3	0.250
	LSD <sub>0.05</sub>	1.3	1	7	30	13	0.006	8	9	75	27	0.001	3.0	0.2	0.051
Piedmont	Cecil A	1.0	4	7	849	37	0.007	1	26	676	354	0.010	57.8	5.8	0.026
	Cecil B	7.9	56	117	635	121	0.143	34	160	526	440	0.053	29.2	5.6	0.228
	Cecil C	13.6	70	112	587	110	0.147	36	239	603	694	0.054	31.4	6.1	0.331
	Cecil D	24.6	145	245	658	190	0.277	89	392	654	945	0.066	33.1	6.3	0.416
	LSD <sub>0.05</sub>	3.9	13	12	36	41	0.019	11	32	94	231	0.009	4.3	0.4	0.045
Piedmont	Tatum A	3.6	11	17	630	56	0.022	4	54	683	419	0.017	44.5	7.5	0.122
	Tatum B	5.0	12	35	603	78	0.046	11	66	533	336	0.027	31.1	5.7	0.207
	Tatum C	5.1	41	31	425	151	0.052	13	171	551	1483	0.019	27.9	6.8	0.221
	Tatum D	15.1	96	156	557	92	0.219	30	283	607	495	0.082	24.4	7.0	0.345
	LSD <sub>0.05</sub>	1.8	3	3	40	13	0.004	3	12	54	77	0.006	2.2	0.4	0.091
Coastal Plain	Emporia A	3.4	18	49	472	56	0.083	14	63	225	120	0.068	15.7	5.1	0.220
	Emporia B	3.8	21	55	425	70	0.102	12	65	199	111	0.077	11.1	5.5	0.236
	Emporia C	9.4	34	63	251	54	0.193	17	76	138	96	0.110	9.1	7.6	0.337
	Emporia D	8.1	35	108	608	95	0.140	26	121	356	161	0.093	11.4	5.9	0.263
	LSD <sub>0.05</sub>	1.3	7	9	32	11	0.008	4	12	29	13	0.004	2.0	0.3	0.070
Coastal Plain	Slagle A	2.8	11	30	379	50	0.062	8	34	142	88	0.053	12.4	5.3	0.241
	Slagle B	3.2	12	36	600	114	0.047	8	56	494	328	0.024	12.2	6.1	0.165
	Slagle C	8.6	39	82	496	59	0.132	18	91	231	109	0.105	14.4	6.3	0.363
	Slagle D	11.0	65	175	702	119	0.195	23	241	573	303	0.103	14.7	6.5	0.334
	LSD <sub>0.05</sub>	2.2	4	4	34	24	0.003	12	10	44	31	0.005	1.8	0.1	0.039
Coastal Plain	Bojac A	4.7	14	44	631	98	0.055	7	176	1111	841	0.030	9.1	7.3	0.299
	Bojac B	8.6	49	100	603	120	0.128	22	215	762	766	0.042	13.7	6.9	0.326
	Bojac C	11.9	115	262	833	174	0.241	43	367	786	436	0.111	19.1	6.0	0.351
	LSD <sub>0.05</sub>	2.8	5	43	100	24	0.015	22	28	145	79	0.006	5.2	0.4	0.061

<sup>†</sup> Water-soluble P.

<sup>‡</sup> Mehlich-1 extractable.

<sup>§</sup> Mehlich-3 extractable.

<sup>||</sup> P saturation ratio as determined by Mehlich-3 extraction.

<sup>#</sup> Ammonium oxalate extractable.

<sup>††</sup> P saturation ratio as determined by ammonium oxalate extraction.

NH<sub>4</sub> oxalate (pH 3), 2-h reaction time in the dark [McKeague and Day, 1966]); (vi) M3-P, M3-Al, and M3-Fe (Mehlich-3 P, Al, and Fe, 1:10 soil/0.2 M CH<sub>3</sub>COOH + 0.25 M NH<sub>4</sub>NO<sub>3</sub> + 0.015 M NH<sub>4</sub>F + 0.13 M HNO<sub>3</sub> + 0.001 M EDTA, 5-min reaction time, filtration with Whatman no. 42 paper [Kuo, 1996]); and (vii) Fe-strip P (1:40 soil/0.01 M CaCl<sub>2</sub> + Fe-oxide coated filter paper strip, 16-h reaction time, followed by dissolving P from the filter paper strip for 1 h in 0.1 M H<sub>2</sub>SO<sub>4</sub> [Chardon et al., 1996]). Extracted P, Al, and Fe were analyzed by inductively coupled plasma-atomic emission spectroscopy. The ratio of Mehlich 3 and NH<sub>4</sub> oxalate extractable P to Al plus Fe (all values in mmol kg<sup>-1</sup>) was expressed as:

$$P/(Al + Fe)$$

and will be referred to as the *Mehlich 3 P saturation ratio* (P<sub>sat</sub><sub>M3</sub>) and *ammonium oxalate P saturation ratio* (P<sub>sat</sub><sub>ox</sub>). Note that this is exactly the same as the traditional soil DPS (degree of P saturation) calculations (Pautler and Sims, 2000) except without the empirical constant  $\alpha$ , which is used to relate soil P sorption capacity to Al<sub>ox</sub> and Fe<sub>ox</sub> and the denominator acts to express the effective total soil P sorption maximum. Because our experiment consisted of a broad range of soil types in which the  $\alpha$  value was unknown, no  $\alpha$  value was used. Beauchemin and Simard (1999) noted that various studies have applied an  $\alpha$  value of 0.5 to all soils, regardless of soil properties. They claimed that the  $\alpha$  value is empiric and needs to be determined for each soil type and experimental conditions. In addition, Beck et al. (2004) recommended that the  $\alpha$  value be omitted from the DPS calculation.

### Simulated Rainfall Study

Dried and sieved soils were poured into wooden runoff boxes approximately 100 by 20 cm by 5 cm in size, replicated three times, leveled, and presaturated 24 h before being placed under a rainfall simulator to ensure that runoff would occur during the rainfall event (SERA-17, 2004). The amount of water necessary to presaturate each soil type was determined by adding water to a box until ponding on the soil surface occurred. That same volume of water was then applied to all boxes containing the respective soil type.

The rainfall simulator consisted of a single Tee Jet HH-SS-50WSQ nozzle (Spraying Systems Co., Wheaton, IL) attached to a 3 by 3 by 3 m metal frame, and calibrated to achieve an intensity of 7.5 cm h<sup>-1</sup> at 90% uniformity. The runoff boxes were placed randomly under the rainfall simulator on steel racks adjusted to a 5% slope. Rainfall events were 30 min long and all runoff was collected in 9-L plastic containers. Runoff subsamples were pipetted in 10-mL aliquots from bulk runoff samples that were being mixed on a stir plate to keep all sediment in suspension. These subsamples were analyzed for DRP (40 mL of runoff filtered through 0.45- $\mu$ m Millipore filter membranes and analyzed by the Murphy and Riley colorimetric method [Murphy and Riley, 1962]).

### Statistical Analysis

The distribution of data was tested for normality by the Shapiro-Wilkes statistic conducted by the SAS univariate procedure (SAS Institute, 1998). All correlation and analysis of variance procedures were conducted by standard procedures using SAS. The linear relationship of soil P with runoff DRP concentrations for each soil type was tested to determine if the relationships (slope and intercept) were significantly different from each other. The null hypothesis was that one equation could be used to describe runoff DRP vs. some soil P parameter. This was tested by using a series of contrast statements in SAS

to determine if the slope and intercept were significantly different based on soil type. In addition, this procedure was also conducted on the same set of soils grouped by physiographic region, providing even greater statistical strength (12 soils and 36 observations for each physiographic province, except for Coastal Plain, which only had 11 soils and 33 observations). Again, the purpose of this was to determine if the slope and intercept for each relationship was significantly different between each physiographic region. Note that all experimental replications were included in such tests, as opposed to mean values.

## RESULTS AND DISCUSSION

### Soil Properties

The background properties of the soils used in the runoff study are listed in Table 1. Although most of the soils exhibited a wide range in WSP, some soil types were limited in the range of M1-P. For example, although the Davidson had a wide range in WSP, the M1-P values were limited relative to the other soil types. This highlights the differences between the two P extracting solutions; specifically, Mehlich 1 can vary in P extracting efficiency as a function of soil type. Presumably, this variation in P extraction efficiency is a result of the differences in P forms among the soils types.

Based on the Virginia Tech Soil Testing Lab guidelines, most of these soils are considered to range from medium (6–18 mg kg<sup>-1</sup>) to very high (>55 mg kg<sup>-1</sup>) in M1-P, although some of the soils are considered low (0–6 mg kg<sup>-1</sup>) and only range up to high (18–55 mg kg<sup>-1</sup>) in M1-P. It is important to keep in mind that these ratings are based on agronomic crop P needs, and do not necessarily reflect potential P loss risk. Ranges in soil pH were typical for agricultural soils with the exception of a Tatum and Emporia soil sample, which had a pH >7.5 (Table 1). As expected, soil clay content was the highest among the three Piedmont soils (Cecil, Tatum, and Davidson), lowest among Coastal Plain soils (Emporia, Slagle, and Bojac), and intermediate among Ridge and Valley soils (Frederick, Groseclose, and Sequoia) (Table 1).

Ridge and Valley and Piedmont soils tended to be dominated more by Fe than Al (63% of samples had Fe<sub>ox</sub> > Al<sub>ox</sub>) while the opposite was true for the Coastal Plain soils (0.09% of samples had Fe<sub>ox</sub> > Al<sub>ox</sub>). In addition, 63% of all samples had more Al extracted by Mehlich 3 than NH<sub>4</sub> oxalate (Table 1). In the case of NH<sub>4</sub> oxalate, amorphous Al is extracted from the soil while Mehlich 3 extracts both crystalline and amorphous Al (due to the NH<sub>4</sub>F; Kuo, 1996), yet removes much less Fe relative to Al compared with NH<sub>4</sub> oxalate. Theoretically then, the difference between M3-Al and Al<sub>ox</sub> would be crystalline Al (such as gibbsite) and, in this case, more Coastal Plain soils contained crystalline Al (73%) than the other soils (54%). The effect (if any) of the degree of Al and Fe crystallinity on how strong P is retained during a rainfall event is unknown.

### Predicting Runoff Dissolved Reactive Phosphorus Concentrations using Soil Phosphorus Extractions

Runoff volumes were not significantly different among soil types. In addition, since there was no sig-



nificant relationship between clay content and runoff volume ( $r^2 = 0.01$ ), correlation procedures were conducted on runoff concentrations and will be referred to as *P losses*. Runoff DRP losses were well related to soil P (Table 2). Various researchers have also shown that soil Fe-strip P, M1-P, M3-P, WSP,  $\text{Psat}_{\text{M3}}$ , and  $\text{Psat}_{\text{ox}}$  can be fairly good predictors of runoff DRP (Torbert et al., 2002; Penn and Sims, 2001; Pote et al., 1996). It appeared, however, that no soil test was well correlated with runoff DRP concentrations from the Bojac soil. Part of the reason for this could be that this was the only soil in which there were only three different samples instead of four (Table 1), providing only nine points for regression instead of 12. Also, this soil type showed a high amount of variability in soil properties such as clay content. The explanation for this lies in the fact that one of the Bojac soil samples was taken from a farm west of the Chesapeake Bay while the other two were taken from the eastern shore of Virginia. Although they were all mapped as Bojac, the Bojac soils west of the bay tend to contain much more clay than those on the eastern shore of Virginia. The variation in Bojac clay content is evident in the official series description data, since the A horizon texture can be loamy sand, loamy fine sand, sandy loam, fine sandy loam, or loam.

Considering only  $r^2$  values among individual soil types, WSP,  $\text{Psat}_{\text{M3}}$ , and  $\text{Psat}_{\text{ox}}$  were the best soil tests for predicting DRP concentrations in runoff (Table 2). Previous studies have also shown that soil WSP,  $\text{Psat}_{\text{M3}}$ , and  $\text{Psat}_{\text{ox}}$  tend to be best correlated to runoff DRP concentrations as well as dissolved P in leachates (Fang et al., 2002; Sims et al., 2002; Maguire and Sims, 2002).

### Evaluation of Soil Tests as a Universal Extractant for Predicting Dissolved Reactive Phosphorus Concentrations in Runoff

Although there is a good relationship between soil test P and runoff DRP for most soils, it would not be practical to determine this relationship for every soil type in question. Therefore, a useful application of this data would be to determine if there is a universal relationship between some soil parameter and runoff DRP concentrations. To investigate this, we distinguished between slopes and intercepts that were statistically different from each other when comparing the linear relationship between different soil types (Table 3). Table 3 shows that, when all soil types are compared with each other, there tends to be a greater number of significantly different intercepts than slopes among the soil P vs. runoff DRP relationships. In other words, within each soil test vs. runoff DRP relationship, the slopes were more similar among different soil types than the intercepts. Based on these results, WSP appears to be the best soil test in regard to applying a universal regression equation for estimating DRP concentrations in runoff from soils (Table 3 shows only six instances in which the slope for the WSP vs. runoff DRP concentration was significantly different when comparing all soil types). This is probably due to the fact that the extracting solution for WSP (deionized water) is more similar

Table 2. Regression equations for the relationship between runoff DRP (dissolved reactive P) concentrations and soil test P for individual soil types. Numbers in parentheses are  $r^2$  values.

Soil type	WSP†	M1-P‡	M3-P§	Fe strip	$\text{Psat}_{\text{M3}}  $	$\text{Psat}_{\text{ox}}\#$
Cecil	$y = 0.015x + 0.06$ (0.83)**	$y = 0.0027x + 0.07$ (0.84)**	$y = 0.0016x + 0.06$ (0.83)**	$y = 0.004x + 0.09$ (0.79)*	$y = 1.4x + 0.04$ (0.88)**	$y = 6.3x - 0.04$ (0.86)**
Tatum	$y = 0.014x + 0.12$ (0.63)*	$y = 0.0022x + 0.14$ (0.74)*	$y = 0.0013x + 0.15$ (0.73)*	$y = 0.008x + 0.11$ (0.82)**	$y = 1.0x + 0.14$ (0.76)*	$y = 2.8x + 0.12$ (0.73)*
Davidson	$y = 0.010x + 0.09$ (0.79)*	$y = 0.0045x + 0.08$ (0.45)*	$y = 0.0026x + 0.04$ (0.71)*	$y = 0.008x + 0.11$ (0.72)*	$y = 1.8x + 0.07$ (0.77)*	$y = 5.4x + 0.05$ (0.62)*
Emporia	$y = 0.016x + 0.17$ (0.55)*	$y = 0.0050x + 0.13$ (0.59)*	$y = 0.0005x + 0.23$ (0.04)	$y = 0.002x + 0.23$ (0.04)	$y = 0.9x + 0.18$ (0.47)*	$y = 2.7x + 0.03$ (0.58)*
Slagle	$y = 0.017x + 0.17$ (0.59)*	$y = 0.0028x + 0.18$ (0.50)*	$y = 0.0009x + 0.20$ (0.43)*	$y = 0.007x + 0.12$ (0.48)*	$y = 1.1x + 0.15$ (0.67)*	$y = 2.3x + 0.12$ (0.91)**
Bojac	$y = 0.005x + 0.28$ (0.18)	$y = 0.0005x + 0.29$ (0.34)	$y = 0.0005x + 0.30$ (0.34)	$y = 0.001x + 0.30$ (0.25)	$y = 0.3x + 0.29$ (0.34)	$y = 0.6x + 0.29$ (0.29)
Frederick	$y = 0.011x + 0.13$ (0.91)**	$y = 0.0011x + 0.18$ (0.57)*	$y = 0.0007x + 0.16$ (0.70)*	$y = 0.002x + 0.19$ (0.52)*	$y = 1.1x + 0.12$ (0.95)**	$y = 2.8x + 0.11$ (0.90)**
Groseclose	$y = 0.007x + 0.17$ (0.77)*	$y = 0.0019x + 0.16$ (0.90)**	$y = 0.0009x + 0.16$ (0.76)*	$y = 0.002x + 0.12$ (0.76)*	$y = 0.8x + 0.16$ (0.76)*	$y = 2.8x + 0.10$ (0.95)**
Sequoia	$y = 0.011x + 0.10$ (0.80)**	$y = 0.0011x + 0.16$ (0.38)	$y = 0.0012x + 0.11$ (0.17)	$y = 0.003x + 0.10$ (0.53)*	$y = 2.1x + 0.04$ (0.55)*	$y = 2.7x + 0.12$ (0.30)

\* Significant relationship at  $P = 0.05$ .

\*\* Significant relationship at  $P = 0.01$ .

† Water-soluble P.

‡ Mehlich-1 extractable.

§ Mehlich-3 extractable.

|| P saturation ratio as determined by Mehlich-3 extraction.

# P saturation ratio as determined by ammonium oxalate extraction.

**Table 3. Number of instances in which slopes and intercepts were significantly different among a comparison of all soil types for each linear relationship between soil test P and runoff dissolved reactive P concentrations. Among all nine soil types, there were 38 possible comparisons for each soil test. Statistical significance was based on  $P = 0.05$ .**

Soil test	Significantly different slopes	Significantly different intercepts
Water-soluble P	6	14
Mehlich-1 P	14	16
Mehlich-3 P	13	18
Fe-P strip	15	17
Degree of P saturation (Mehlich-3)	11	15
Degree of P saturation (NH <sub>4</sub> oxalate)	15	15

to the simulated rainfall water (tap water) than the Mehlich 1 and 3 solutions, NH<sub>4</sub> oxalate, or the Fe-impregnated strips. Similarly, Vadas et al. (2005) found that 17 of 20 soils did not have significantly different slopes for the soil WSP vs. runoff DRP relationship in reviewing several previously published runoff studies. The range of WSP slopes for their study was similar to results from our study (0.06–0.183 and 0.06–0.170 mg P L<sup>-1</sup>, respectively), not including the Bojac soil since the correlation between WSP and runoff DRP concentration was not significant for that soil type (Table 2). In addition, the overall measured soil WSP slope as determined by Vadas et al. (2005) was also very similar to that determined in this study (0.0120 and 0.0125, respectively).

The individual comparisons between soil types among slopes from the WSP vs. DRP relationship is shown in Table 4. Based on the fact that only six of the 38 possible comparisons among WSP slopes were significantly different (Tables 3 and 4), the WSP test may serve as the best possible universal estimate of runoff DRP concentrations. One potential problem is calculating the intercept for such an estimate. Vadas et al. (2005) was interested only in the “runoff coefficient” (slope) of runoff DRP relationships, and thus ignored differences in intercepts.

While the slopes for the WSP vs. runoff DRP relationship are for the most part the same between soil types, the intercepts seem to be unique to each soil type (Table 3). Some estimate of the  $y$  intercept would be necessary in using soil WSP to estimate runoff DRP concentrations. One possible solution would be to determine one point (i.e., soil WSP and runoff DRP) for the soil type of interest and then assume a slope of 0.0125 (i.e., the slope for the WSP vs. runoff DRP relationship among all soils). From this assumed slope and the mea-

sured single point, the  $y$  intercept can be calculated. The disadvantage of this approach is that one would not only have to measure runoff DRP concentrations for one soil among each soil type of interest, but the accuracy of the calculated  $y$  intercept is dependent on the natural variability of the WSP vs. runoff DRP relationship.

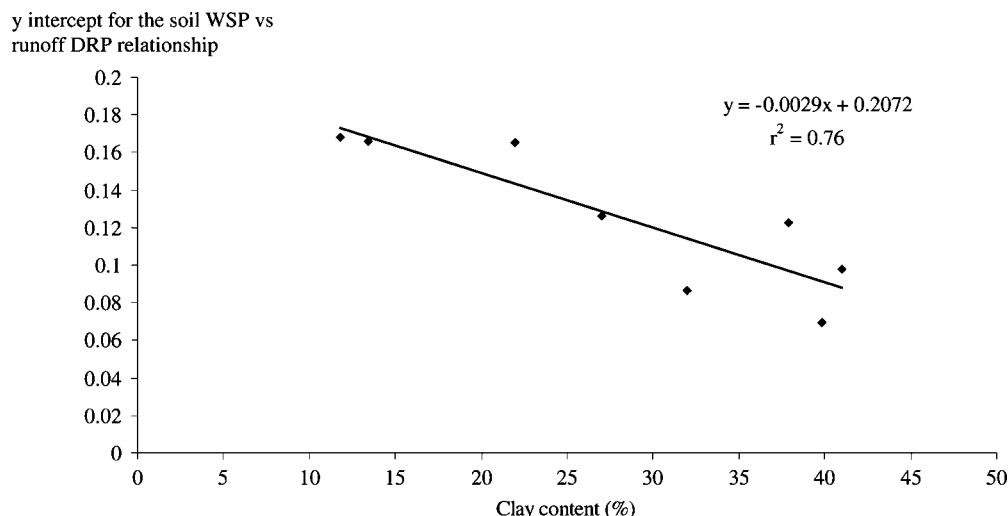
Perhaps the best solution would be to calculate a  $y$  intercept based on some other soil property. Figure 1 suggests that the  $y$  intercept for each soil type for the relationship between soil WSP and runoff DRP is well related to soil clay content. Note that this figure excludes the Bojac soil type due to the fact that soil WSP was not significantly correlated to runoff DRP concentrations. Using the regression equation in Fig. 1, the  $y$  intercept for the soil WSP vs. runoff DRP relationship could easily be estimated from clay content (which is available for each soil type in the soil survey). This estimated  $y$  intercept could then be used with the assumed slope of 0.0125 to develop an equation for estimating the concentration of DRP in runoff from soils. Since the more coarse-textured soils (i.e., Coastal Plain soils) had greater  $y$  intercepts than the more fine-textured soils (Fig. 2), and assuming that all of these soils have the same slope for the WSP vs. runoff DRP relationship, this suggests that Coastal Plain soils would yield a higher concentration of DRP in runoff than the fine-textured soils for a given soil WSP level. This trend has also been shown in a study by Cox and Hendricks (2000) in which they conducted rainfall simulations on both Coastal Plain (5% clay) and Piedmont (32% clay) soils of North Carolina and correlated M3-P to runoff dissolved P for each set of soils. Results showed that for a given level of soil M3-P, the Coastal Plain soils yielded more dissolved P in runoff than the Piedmont soils.

In addition to using clay content as a predictor of the  $y$  intercept for the soil WSP vs. runoff DRP relationship, soil Fe<sub>ox</sub> was also related to the  $y$  intercept by the linear equation:  $y$  intercept =  $-0.00006(\text{Fe}_{\text{ox}}) + 0.172$  ( $R^2 = 0.68$ , significant at the 0.05 probability level); however, Fe<sub>ox</sub> was co-correlated with clay content [clay content =  $0.0176(\text{Fe}_{\text{ox}}) + 14.69$ ;  $R^2 = 0.64$ , significant at the 0.05 probability level]. This co-correlation makes it difficult to ascertain the meaning of the perceived effect of soil texture on the soil WSP–runoff DRP relationship. In other words, the significant correlation between clay content and the  $y$  intercept may only be a result of the co-correlation between Fe<sub>ox</sub> and clay content. Using this same set of soils, Penn et al. (2005) showed that clay content was only significantly correlated to P adsorp-

**Table 4. Statistical  $P$  values indicating significant differences between the slopes among comparisons of the linear relationship for soil water-soluble P vs. runoff dissolved reactive P concentrations between all soil types.**

Soil type	Frederick	Groseclose	Sequoia	Davidson	Cecil	Tatum	Emporia	Slagle
Groseclose	0.160							
Sequoia	0.990	0.410						
Davidson	0.660	0.370	0.770					
Cecil	0.140	0.0003†	0.380	0.040†				
Tatum	0.420	0.030†	0.580	0.210	0.650			
Emporia	0.410	0.090	0.500	0.260	0.960	0.780		
Slagle	0.130	0.007†	0.260	0.059	0.540	0.410	0.750	
Bojac	0.260	0.640	0.350	0.380	0.040†	0.090	0.120	0.030†

† Significantly different slope at  $P$  value  $<0.05$ .

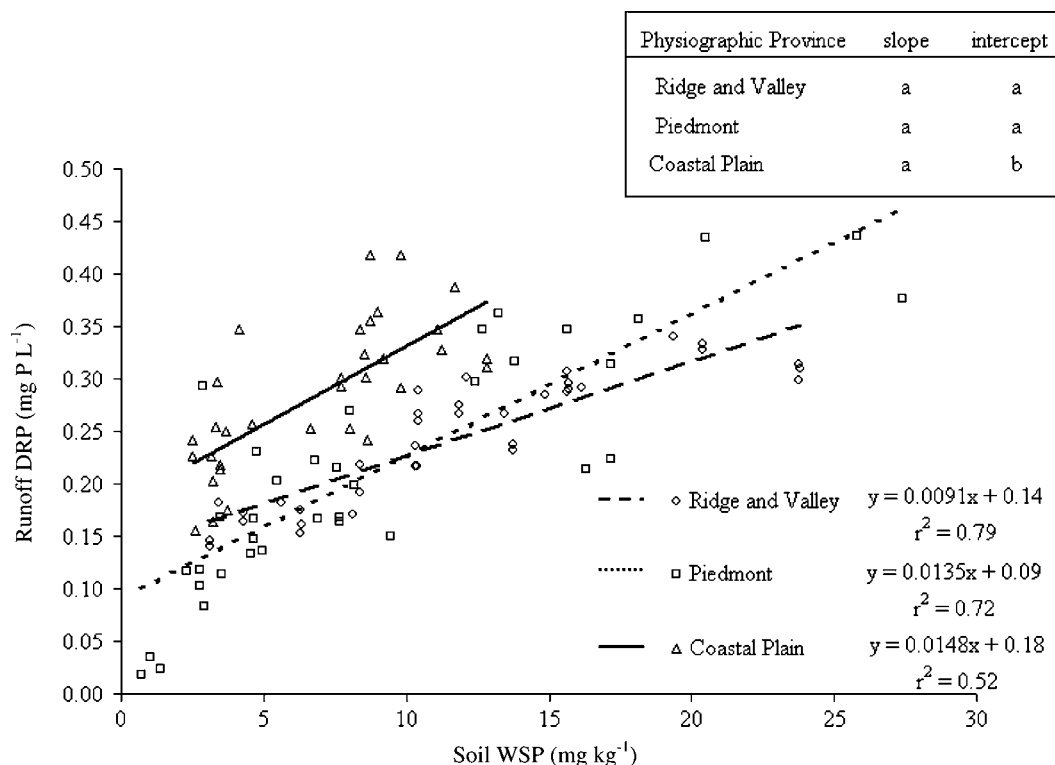


**Fig. 1.** Relationship between average soil clay content and the y intercept for the soil WSP (water-soluble P) vs. runoff DRP (dissolved reactive P) relationship for each soil type.

tion, not desorption, as estimated by the percentage of P retained on P-saturated samples after five sequential desorptions with 0.01 M CaCl<sub>2</sub>. As clay content does not affect soil P desorption (the WSP–runoff DRP y intercept would be a function of desorption potential), it is more likely that the y intercept for the WSP–runoff DRP relationship is a direct function of Fe<sub>ox</sub> and not clay content. It is impossible however, to directly attribute this observation to a single variable such as clay content or Fe<sub>ox</sub> in this study. By conducting a statistical path analysis on 28 benchmark Oklahoma soils, Zhang et al.

(2005) showed that, although clay content was significantly correlated to soil P adsorption capacity, this correlation was only indirect, since soil Fe<sub>ox</sub> and Al<sub>ox</sub> were the only variables significantly and directly correlated to P adsorption capacity. They only examined P adsorption in the study and not P desorption. The results of the current study are in contrast to Penn et al. (2005), in which soil Fe<sub>ox</sub> was not significantly correlated to P desorption.

It is interesting to note that Fe<sub>ox</sub> was significantly and negatively correlated to the y intercept of the WSP–runoff DRP relationship while Al<sub>ox</sub> was not. This sug-



**Fig. 2.** Relationship between soil WSP (water-soluble P) and runoff DRP (dissolved reactive P) concentration for all soils as grouped by physiographic region. Lowercase letters in inset indicate statistical significance ( $P = 0.05$ ) of slope and intercept among the physiographic region. Physiographic regions that possess the same letter are not significantly different from each other.

gests that soil Fe and Al may differ in P retention potential—specifically that P bound with Fe is less desorbable. Past studies have pointed toward the idea that P-saturated Al components are able to desorb (or release) P more easily than P-saturated Fe components, most likely because phosphate forms a stronger bond with Fe than with Al (Aura, 1978). For example, Hartikainen (1982) conducted a study on 104 Finnish soils to relate WSP parameters to other soil properties. Soil WSP was most closely connected with loosely bound P and Al-related P, while the correlation of WSP with Fe related P was poor and nonexistent with the reductant soluble fraction. Hartikainen (1982) noted that “the results imply that WSP is primarily controlled by the ratio of Al related P to Al; this explained 77% of the variation in the loosely bound P and also illustrates the role of the Al related P fraction in determining the concentration of phosphate in the soil solution.” The ratio of Al-related P to Al can be thought of as the P saturation of the Al component of the soil. Other studies have also shown that P bound or adsorbed with Fe is more stable (less desorbable) than Al-related P (Beauchemin et al., 1996; Le Mare, 1982).

#### **Differences in the Soil Water-Soluble Phosphorus–Runoff Dissolved Reactive Phosphorus Relationship Based on Physiographic Province**

Another similar approach to estimating DRP concentrations in runoff is found in grouping soils by physiographic province. Figure 2 shows that when the soils used in this study are split into three different groups based on physiographic region, the slope for each WSP vs. runoff DRP relationship are not statistically different from each other. This observation is consistent with the fact that there were very few significantly different slopes among all soil types for the relationship between WSP and runoff DRP (Table 3). In addition, the average slope for the three regions was approximately equal to the “universal slope” determined from averaging each soil type, and also to that of Vadas et al. (2005). As observed with the WSP vs. runoff DRP relationships among individual soil types, the intercepts of such relationships varied more than the slopes (Table 3, Fig. 2). Specifically, although the slopes among the three physiographic regions for the WSP vs. runoff DRP relationship were not significantly different, the intercept for the Coastal Plain soils was significantly greater than that for the Piedmont and Ridge and Valley soils, which were not significantly different from each other (Fig. 2). This verifies our previous hypothesis that Coastal Plain soils will yield a significantly greater concentration of DRP in runoff (for a given WSP content) than Piedmont and Ridge and Valley soils, presumably due in part to clay or Fe<sub>ox</sub> content. Again, this supports the findings of Cox and Hendricks (2000), but for different reasons: they found that Coastal Plain soils had the same intercept and a greater slope than Piedmont soils, while our results were opposite (i.e., same slope but a greater intercept than Piedmont and Ridge and Valley soils).

## **CONCLUSIONS**

Overall, among each soil type, soil WSP, Psat<sub>M3</sub>, and Psat<sub>ox</sub> were best correlated to concentrations of DRP in runoff (based on  $r^2$ ). Although other studies have also shown that these three soil extractions for P are well related to runoff DRP, the relationship typically varies based on soil type. Presumably, this variation occurs because of differences in P forms among soils. In general, the relationship between soil P and runoff DRP is unique for each soil type. Data from this study showed that slopes and intercepts for the relationship between soil P and runoff DRP were significantly different among many soil types for most measures of soil P (M1-P, M3-P, Fe-strip P, Psat<sub>M3</sub>, and Psat<sub>ox</sub>). Slopes from the soil WSP vs. runoff DRP linear relationship were not significantly different, however, for nearly all of the possible comparisons between soil types. The range (0.06–0.17) and overall soil WSP slope (0.0125) measured in this study was also nearly the same as that determined by Vadas et al. (2005). These results suggest that a universal slope for soil WSP of approximately 0.0125 mg DRP L<sup>-1</sup> can be used to estimate runoff DRP concentrations.

While soil WSP slopes were mostly the same, the y intercept for the WSP vs. runoff DRP relationship was unique to most soil types; however, the y intercept for a soil type could be estimated by one of two possible methods: (i) determine one point on the soil WSP vs. runoff DRP concentration, assume the universal slope of 0.0125, and back calculate the intercept, or (ii) estimate the y intercept based on soil clay content using the relationship developed here. The second option is a result of the fact that soils with lower clay content tend to have a higher y intercept in regard to the soil WSP vs. runoff DRP linear relationship. As expected then, when soils were grouped based on physiographic region, slopes were not significantly different for the soil WSP vs. runoff DRP relationship, while Coastal Plain soils exhibited a significantly greater intercept than the more fine-textured Piedmont and Ridge and Valley soils. Therefore, Coastal Plain soils tend to have a more “effective” WSP concentration in that, for a given soil WSP level, unamended Coastal Plain soils will yield a higher concentration of DRP in runoff than Piedmont and Ridge and Valley soils.

Although this study concludes that soil WSP can be used as a universal extractant for predicting DRP losses from acidic, noncalcareous soils, this is not, however, meant to take the place of a more comprehensive P loss assessment tool such as the P index. The use of WSP as a universal extractant is only meant to refine the component of P loss models that incorporate the use of a soil P vs. runoff DRP relationship.

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